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PASSIVE INTERMODULATION IN PASSIVE RADIO FREQUENCY FILTERS

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Matias Pihlman
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ABSTRACT

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Supervisors: Heikki Mattila, Marko Leinonen
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The objective of this this Bachelor's thesis was to study the passive intermodulation distortion generated in nonlinear radio frequency filters. The thesis was commissioned by OY LM Ericsson AB site in Oulu. The first aim of this thesis was to build a measurement setup with high dynamic range so that intermodulation products can be reliably measured. The second aim was to compare how well the obtained measurement results would match theoretical third order passive intermodulation models.

Firstly a measurement setup for two-tone measurements was built from laboratory radio frequency components. Two test signals were created, combined and fed to the input port of the device under test. These two high power signals create spurious signals called intermodulation products when they are fed to a nonlinear device. A power sweep measurement was done for nine different radio frequency filters and intermodulation product levels were measured under different temperatures using three different tone spacings.

A study of filter types and causes of passive intermodulation distortion was required in order to properly analyse the results. Component choices for the measurement setup were explained. The linearity and sensitivity of the measurement setup was also checked.

The measurement setup with a high dynamic range and good linearity was built. The passive intermodulation distortion was measured and characterized for nine radio frequency filters successfully. The results were compared to theoretical models and analysed from several points of view. Overall intermodulation products in all nine filters behaved like expected. The analysis showed that the measured data fit passive intermodulation models well and the measurements were done accurately.

Keywords: Passive intermodulation, Filter, Linearity, Small cell, Base station

TIIVISTELMÄ

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Tämän opinnäytetyön tavoitteena oli tutkia passiivista keskeismodulaatiota, joka syntyy epälineaarisissa radiotaajuus suodattimissa. Opinnäytetyön aiheen tarjosi OY LM Ericsson AB ja työ tehtiin Ercissonin Oulun toimipisteellä. Ensimmäinen tavoite oli suunnitella testiympäristö isolla dynaamisella alueella, jotta keskeismodulaatio signaalit saadaa luotettavisti mitattua. Toinen tavoite oli verrata mitattuja tuloksia teoreettisiin kolmannen asteen keskeismodulaatio malleihin ja tutkia miten hyvin ne vastaavat niitä.

Aluksi koottiin testiympäristö laboratorio käyttöön tarkoitetuista radiotaajuus komponenteista. Testiympäristöllä luotiin kaksi testisignaalia, jotka yhdistettiin ja syötettiin testattavana olevan suodattimen sisääntuloon. Epälineaarisissa komponenteissa muodostuu ei-toivottuja summataajuuksia, kun kaksi isotehoista signaalia, jotka ovat lähellä toisiaan taajuustasossa, syötetään komponentin sisääntuloon. Yhteensä yhdeksän suodattimen keskeismodulaation tehotasot mittattiin, kolmessa eri lämpötilassa, kolmella eri testisignaalien kaistanleveydellä, usealla eri testi signaalien tehotasolla.

Taustatutkimusta tehtiin mittauksissa käytetyille suodatinteknologioille ja keskeismodulaation syntytavoille. Testiympäristöstä tutkittiin sen omaa lineaarisuutta ja mittausherkkyyttä.

Työssä saatiin koottua tarpeeksi herkkä testausjärjelmä, jolla mittaukset saattin luotettavasti suoritettua. Mitattuja tuloksia verrattiin teoreettisiin malleihin useasta eri näkökulmasta. Lopputulokseksi saatiin varmistus, että keskiesmodulaatio mitatuissa komponenteissa noudattaa teoreettista kolmannen asteen mallia.

Asiasanat: Linearisuus, Radiotaajuus, Suodatin, Keskeismodulaatiosärö

PREFACE

This thesis was commissioned by OY LM Ericsson AB Oulu site during spring 2016. I want to thank Ericsson for providing me the subject for my thesis work. I had great equipment to work with and the general atmosphere at the office was always very positive and supportive.

Huge thanks goes to my supervisor Marko Leinonen from Ericsson. He provided me with feedback, which helped me a lot with this thesis. He was always available if I had any questions. I also want to thank my supervising teacher Heikki Mattila who also provided me feedback of this thesis.

Big thanks to my family who were very supportive throughout my studies.

April 2016, Oulu.

Matias Pihlman

CONTENTS

VOCABULARY

3GPP	3rd generation partnership project
BAW	Bulk acoustic wave
CW	Continuous wave
dB	Decibel
dBc	Decibels relative to the carrier
dBm	Decibel-milliwatts
DC	Direct current
DUT	Device under test
FDD	Frequency-division duplexing
GHz	Gigahertz (thousand Megahertz)
Hz	Hertz
IDT	Interdigital transducer
IIP	Input intercept point
IL	Insertion loss
IM	Intermodulation
IMD	Intermodulation distortion
IP	Intercept point
kHz	Kilohertz (one thousand hertz)
LA	Local area
LCD	Liquid-crystal display

LTE	Long term evolution
MHz	Megahertz (one million hertz)
OIP	Output intercept point
PA	Power amplifier
PIM	Passive intermodulation
PIMD	Passive intermodulation distortion
RBW	Resolution bandwidth
RF	Radio frequency
RL	Return loss
RX	Reception/receiver
SAW	Surface acoustic wave
SMR	Solidly-mounted resonator
TDD	Time-division duplex
TS	Technical specification
TX	Transmission/transmitter
VBW	Video bandwidth

1 INTRODUCTION

We are currently living in the time when the use of mobile phones and mobile data usage is increasing all the time. Users are demanding faster data transfer rates and a better network coverage. And to meet the demands, mobile operators need to deploy mobile base stations.

In large urban cities macro base stations are used to provide a network coverage but these cannot always provide a sufficient coverage inside the building and that is where small base stations come into use. These base stations are small in physical size, operate on a lower output power than a macro station, thus consuming less power, and are cheaper in price, making them ideal for an indoor use because multiple units can be used to provide a great network coverage.

Good hardware is the base for making a good electronic device and this of course applies to base stations, too. Component evaluation is an important part of the manufacturing process and ensuring that the end product will meet the global performance standards and the internal performance requirements of the company.

Some of the hardware performance data can be obtained from simulation and from a component manufacture’s test data, but unforeseen issues might occur while testing real components and passive intermodulation (PIM) is one of those phenomena. There are multiple factors that can generate PIM and the cause cannot always be isolated to just one of these.

A two-tone measurement setup was built since one of the PIM factors is having two relatively high power continuous wave (CW) signals that are combined and fed to an input of the device under test (DUT). This thesis studies the devices and equipment that were used to build the measurement setup and will explain their purpose in it.

PIM can become to be the system limiting factor by interfering with intended communication signals and thus reducing the capacity and range of a communications system. One of the main objectives of this thesis was to compare the measured test results to theoretical 3rd order passive intermodulation models and see how well they follow them. A slope ratio between the measured results and theoretical models and the coefficient of a determination value for the measurement results were also analysed.

Another objective was to observe what kinds of effects tone spacing, measurement temperature and measurement frequency have on PIM results. A two tone measurement is a good way to verify the PIM effect but it does not necessarily reflect end product results since the base stations use wide band signals for data transmission.

A study of passive intermodulation and its causes was required to acquire a better understanding on how to compare and use measurement results. Commonly used filter types and filter technologies that are used in radio frequency filters were described in order to obtain a better knowledge of phenomena that occur within them. Also, it was necessary to study how to build a high dynamic range measurement setup so that the measurements can be conducted accurately and reliably.

This thesis work was commissioned by Ericsson’s Oulu site. It was started in 2012 and it mainly focuses on the research and development of a small cell base station. OY LM Ericsson AB was founded in year 1876 in Stockholm, Sweden by Lars Magnus Ericsson as a telegraph repair workshop (1). Ericsson has a long history in telecommunications and in 2015 it had over 116,000 employees worldwide (2).

2 FILTERS AND PASSIVE INTERMODULATION MODELS

Intermodulation (IM) is a phenomenon that occurs in all nonlinear radio frequency (RF) components to some degree. This means that the output signal of the component is not directly proportional to the input signal of the component. In macro base stations power amplifiers are generally the most nonlinear components and intermodulation caused by the power amplifier can be filtered out. Filters used in small cell products are thought to be linear components because the power levels used for signal transmission are considerably lower than the ones used in macro base stations.

Small cell base stations have recently become more widely used and for this reason intermodulation generated by filters has not been researched as much. Radio frequency filters are passive components and they may generate passive intermodulation (PIM). A component is defined as a passive one if it does not require source energy to perform its intended function. This thesis focuses on PIM in filters used in the transmission chain.

Passive intermodulation distortion (PIMD) is a weakly nonlinear effect and can become the system limiting factor in communication systems by interfering with intended communication signals (3). PIM components cannot be removed because the filter is the last component before the antenna thus the only way to develop highly linear systems is to take PIM into account during the development phase.

Communication signals are transmitted on a high frequency over the air. This leads to a loss in signal strength as signals travel through the air and radio receivers must be able to detect attenuated signals. This means that the receivers must be extremely sensitive, and any interference from spurious signals in the receiver band of a system increases the level of a minimum detectable signal (3).

2.1 Filters, filter types and technologies

In base station hardware filters are used to allow communication signals to pass and to reject unwanted signals. It is necessary to minimize unwanted signals so that the end product can meet the requirements set by the Federal Communications Commission. Filters can be either active or passive but passive filters are used in radio frequency design due to the limited bandwidth of active filters. Filters have four common types that can be defined:

- Low pass filter
- High pass filter
- Band pass filter
- Band rejection filter

Like the name indicates, a low pass filter only allows signals below a determined cut off frequency to pass and a high pass filter does the opposite as it rejects all signals below the determined cut off frequency. A band pass filter only allows a certain range of frequencies to pass and rejects the rest of them. A band rejection filter is used to reject signals within a certain band (4). This thesis focuses on band pass filters as they are used to filter signals before the transmission antenna.

Every electronic component will attenuate signals going through them. For filters, the insertion loss (IL) is used to describe a pass band attenuation in decibels (dB). The decibel is a logarithmic unit and in this case it is used to express the ratio of input and output power. The bandwidth of a filter in RF applications is typically defined by the 3 dB or 1 dB (or both) attenuation at a signal level on either side of the center frequency, though the 3dB point is more commonly used.

Other important parameters are rejection levels on stop bands and a skirt steepness of the filter. A stop band rejection describes how many decibels unwanted signals are attenuated. A skirt steepness is used to describe how many dB/MHz a signal is going to be attenuated when it moves outside of the pass band. Most of the important filter characteristics are shown in FIGURE 1.

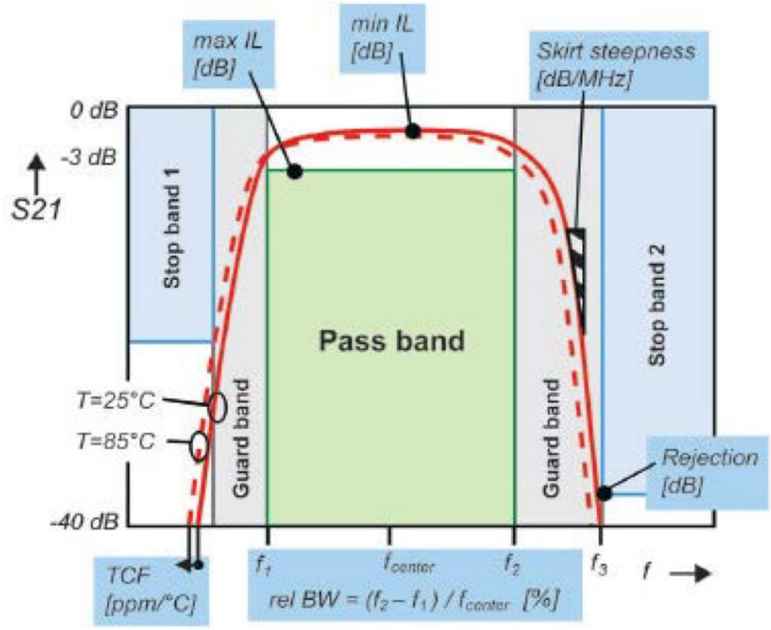

FIGURE 1. Illustration of a band pass RF filter performance characteristics (5)

A guard band is a narrow frequency range and it may be placed on both sides of the pass band to ensure that simultaneously used communication channels do not interfere with each other, which would lead to a decrease in quality on both transmissions.

2.1.1 SAW filter

Surface acoustic wave (SAW) is a filter technology which is commonly used in mobile devices that require a high integration level. Typical characteristics for SAW filters are a low insertion loss, a good stop band rejection and an ability to achieve wide bandwidths. SAW filters are considerably smaller in physical size than traditional cavity and ceramic filters (6). A SAW filter can be used up to 3 gigahertz (GHz) frequencies.

Acoustic wave filters are based on piezoelectric materials and common substrate materials for SAW filters are lithium tantalate ($LiTaO_3$), lithium niobate ($LiNbO_3$) or quartz. All these materials have their piezoelectric and acoustic properties well characterized (8).

When an electric field is applied to the piezoelectric material, it applies mechanical stress to the crystals that are in the piezoelectric and creates acoustic waves. Acoustic waves travel at velocities of 3000 to 12000 m/s creating large delay to the otherwise fast moving RF signals. The waves are confined to create standing waves with high quality factors and are the basis of frequency selectivity and low loss. This transformation from electric wave to acoustic wave and vice versa is called transduction (7). Interleaved metal interdigital transducer (IDTs) are used to convert the input signal into acoustic wave that travels on top of the piezoelectric substrate to another IDT that converts the acoustic wave back to electric signal as shown in FIGURE 2.

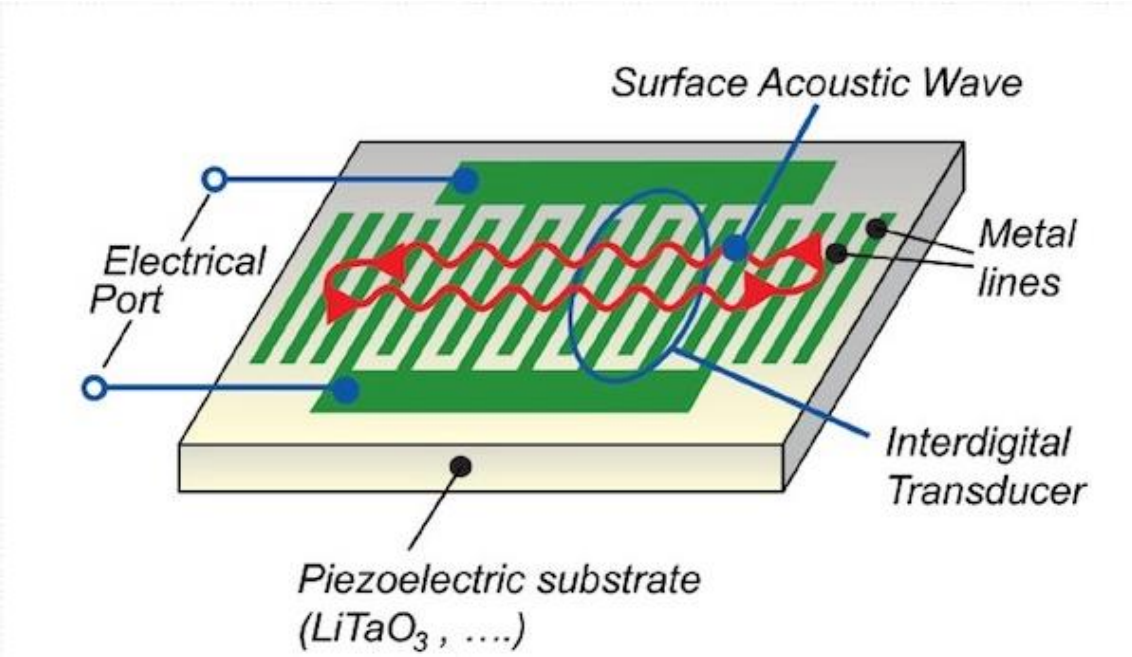

FIGURE 2. Basic SAW filter (6)

When voltage is introduced to the left port in FIGURE 2, the gaps in between electrodes generate electric fields and the piezoelectric effect turns them into mechanical stress creating acoustic waves. The fields and stresses can keep alternating in sign. Thus they keep the acoustic wave moving because the electrodes have alternating connections. The right port will receive these acoustic waves and will turn them back to voltage.

SAW filters are cheap to manufacture and they deliver a great performance on low RF frequencies. But on frequencies above 1 GHz, they start to lose some of their selectivity and above 2.5GHz they are only able to meet very modest performance requirements (6). $LiTaO_3$ and $LiNbO_3$ substrates are both strongly pyroelectric and they have a poor mechanical strength. Due to pyroelectricity, heating or cooling these materials rapidly will make them generate temporary voltage at the surface. SAW filters also have poor electrostatic discharge ratings because the electrodes are exposed to air and have small gaps between them. This can cause discharge arcing at the surface (8).

A temperature-compensated (TC-SAW) filter was created to improve performance at higher temperatures. The IDT structure is overcoated with layers, which help to increase stiffness, but the additional layers make the manufacturing process more complex. This leads to an increased price compared to normal SAWs but TC-SAWs are still less expensive than bulk acoustic wave (BAW) filters.

2.1.2 BAW filter

Bulk acoustic wave (BAW) filters are commonly used in mobile devices like SAW filters. BAW filters are used where SAW/TC-SAW filters cannot deliver a sufficient performance. BAW filters are well suited for frequencies ranging from 1.5 GHz to 5.5 GHz and in this way they are supplementing SAW type filters rather than replacing them.

The substrate material does not play a major role for BAW filters and the only real requirements are a good mechanical robustness and a flat and smooth surface. Usually, dielectric materials with a low dielectric constant and loss are used, such as high-resistivity silicon (Si) delivering the best performance for its cost. Other materials include quartz, glass, alumina and sapphire (9).

In a BAW resonator thin film resonators are used to generate vertical standing waves within the piezoelectric material, which is typically made out of aluminium nitride (AlN). A piezo layer is placed on top of the substrate between two electrodes that are used to excite the acoustic waves (FIGURE 3). By altering the thickness of the piezoelectric slab and the mass of the electrodes, the resonance frequency of the filter can be tuned (6)(9).

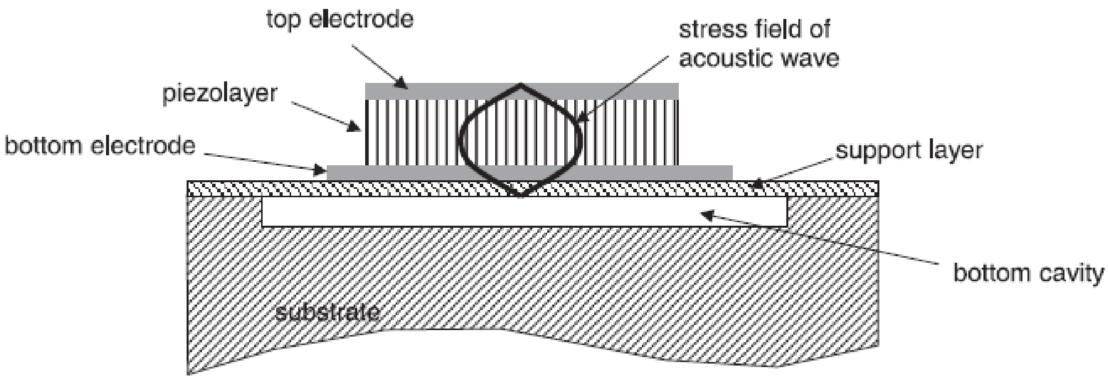

FIGURE 3. Basic BAW resonator (10)

Solidly-mounted resonator (SMR) is configuration architecture for BAW filters. BAW-SMR has an additional acoustic Bragg reflector layer, which consists of acoustic mirrors. The mirrors have altering high and low impedance values and they are stacked on top of each other. The mirror thickness is equivalent to a quarter wavelength at the main resonance frequency (10). This layer is used preventing the acoustic wave from escaping into the substrate (**Virhe. Viitteen lähdettä ei löytynyt.**). A low insertion loss can be achieved with this type of filter because it has high density acoustic waves and its structure traps acoustic waves well.

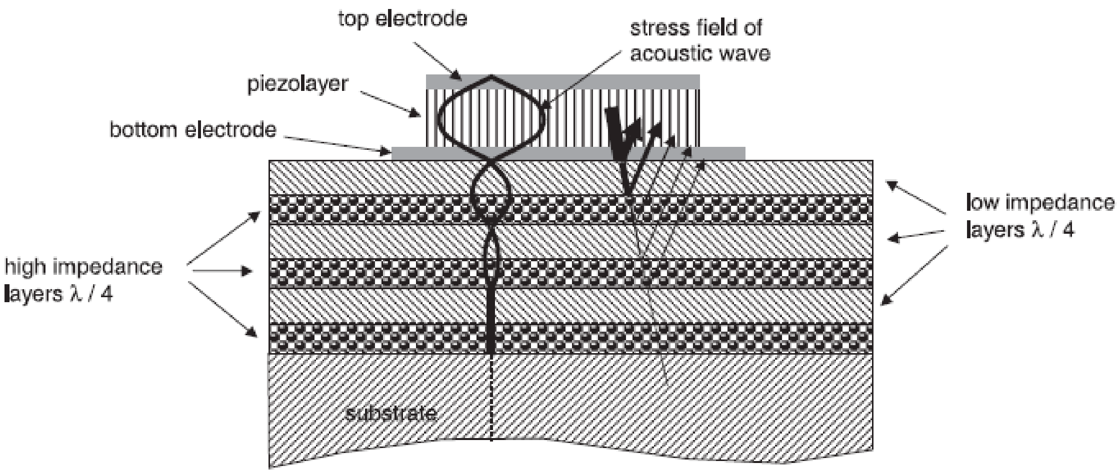

FIGURE 4. Schematic cross section of BAW-SMR (10)

BAW type filters are more expensive to manufacture than SAW types because the filter structure is more complex and requires more processing steps. However, they are the only viable option for challenging long-term evolution (LTE) bands where a good rejection attenuation and steep filter skirts are needed. In addition, BAW substrate materials have a lower temperature coefficient of frequency, which means that in BAW filters frequency drifts less than in SAW filters when temperature changes.

2.2 Causes of intermodulation distortion

Multiple factors can cause intermodulation in a wireless system. Passive intermodulation is a form of intermodulation distortion that occurs in passive components such as coaxial connectors and cables, feeder lines, antenna elements, isolators, switches and filters. All these mechanical components are nonlinear and the nonlinearity makes it possible for two or more signals to mix or multiply together creating interfering signals, which are related to the original signals (12).

A number of things can give rise to nonlinearity that may cause PIM effects. Some of the most common ones are oxidation in joints where dissimilar metals meet, braid in feeder lines outer conductor providing metallic interfaces that can generate PIM, connections made with poor connectors or poorly assembled connectors, dirt in connectors, loose connections or irregular connect areas, use of ferromagnetic metals (for example iron, nickel, steel) and spark discharges (11). Other factors are the age of the component, which tends to increase PIM, and environmental conditions, such as salt air or polluted air. A constant temperature fluctuation or an excessive vibration can worsen PIM effects.

Most of these effects fall well below thermal a noise level because the signals, which give rise to them, are often very small spurious signals. Problems arise in systems that use a shared antenna trace for both a transmitter (TX) and a receiver (RX). Most modern cellular small cell base stations are built using this design, which is shown in FIGURE 5.

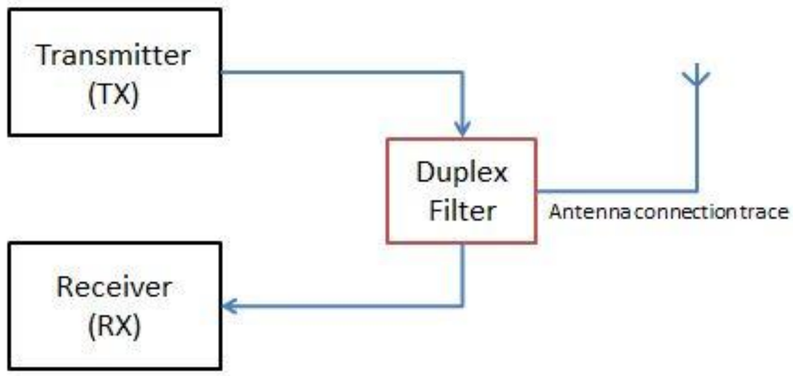

FIGURE 5. Block diagram of basic FDD transceiver

PIM generated in the frequency division duplexing (FDD) filter may reduce the sensitivity of a receiver by raising the noise floor or by blocking signals. As an example the levels of intermodulation products may be -100 to -120 decibels relative to the carrier (dBc) (11). In small cell base stations, the receiver sensitivity needs to be better than -117 dBc based on standard requirements.

In FDD systems the transmitter and the receiver use different carrier frequencies and they both can operate at the same time. Two different pass bands are needed and these are often separated with a narrow guard band called a duplex gap. Time-division duplexing (TDD) systems use the same frequency band for the transmission and reception. Communication signals are separated from each other by assigning non-overlapping time slots in the time domain for transmission and reception. During transmission the receiver is not active and when transmission is complete, the receiver will become active and the transmitter is deactivated to improve the receiver sensitivity and to lower current consumption.

2.3 PIM models

The frequency bands specified by the 3rd generation partnership project (3GPP) have broad bandwidths from tens to hundreds of megahertz. A broad bandwidth enables the use of multiple LTE carriers at the same on the same band. When two or more high power signals are combined and fed into an input of a nonlinear passive component or element, the nonlinearity may cause the signals to mix or multiply with each other creating new signal components that are related to the input ones (11). These new signals components are called harmonic frequencies and IM products.

A two tone measurement is often used for PIM testing. Two continuous wave (CW) signals at frequencies f_1 and f_2 with same power levels are applied into a DUT input port and from an output port IM products can be seen (FIGURE 6). IM products are usually referred to by their order, which is the number of times a product within the output is multiplied (12)(11). The third order IM product (IM3) is usually the most critical one because it may fall within the TX band if the band is broad enough and the tone spacing is narrow enough. IM5 and IM7 products need to be taken into account when defining filter rejection requirements.

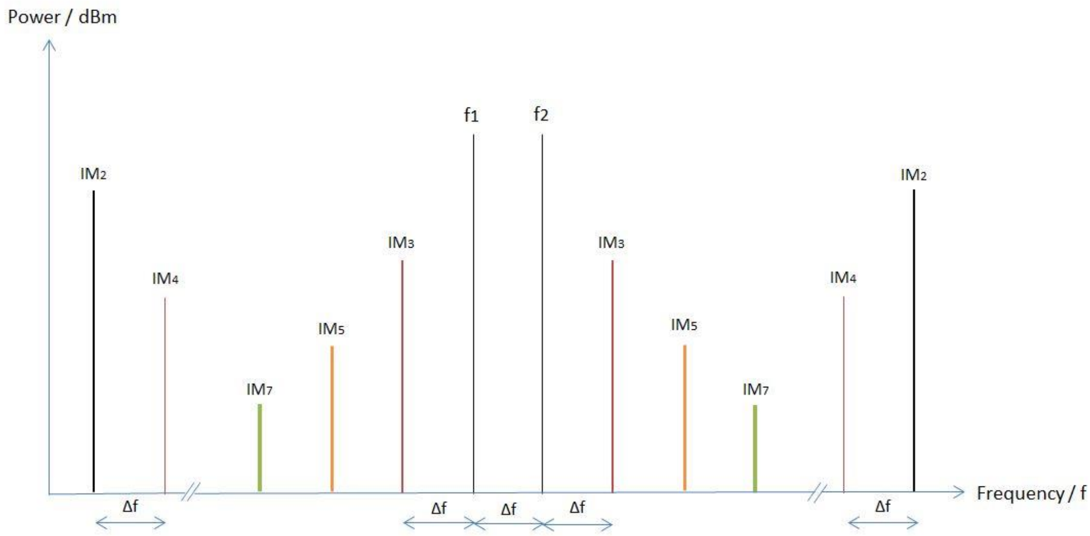

FIGURE 6. Frequency spectrum of PIM nonlinearities

2.3.1 Even order

Even order IM products, which include e.g. IM2, IM4, and IM6, are usually not interfering with any wanted signals because they are far away from the pass band of the filter. Even order IM product frequencies can be calculated with FORMULA 1 but the result is always a very low frequency or a relatively high one. Lower IM2 and IM4 products are in most cases below frequencies of couple of hundred MHz thus not disturbing any common RF devices. Also, a simple high pass filter can be used to suppress these lower side IM products efficiently.

Earlier cellular systems used operational frequencies between 1 and 2 GHz and thus higher IM2 and IM4 products could be ignored because their frequencies are typically around 4 – 8 GHz. Nowadays the used cellular frequency bands are very crowded and this has led new higher frequencies to be used for communication where more spectrum is available. The most currently used RF filters have a good wide band attenuation on these frequencies. If additional filtering is needed, then a low pass filter can be used to filter out these high frequency IM products.

Harmonics are integer multiples of the original input signals. The input signal is often called the fundamental frequency or the first harmonic frequency. The second harmonic signal has twice the frequency of the fundamental one and the third harmonics has three times and so on. In theory a signal can have an infinite number of harmonics but in practice only the 2^{nd} and the 3^{rd} might be of concern because the fundamental is on such a high frequency that higher harmonics will be generated on frequencies that are not used by any device or system.

2.3.2 Odd order

Odd order IMs, which include e.g. IM3, IM5, IM7, are dominating IM products because they are the ones closest to the usable frequency band of an application. The IM product order tells how many times the product within the output is multiplied. Their power level can be expressed in terms of absolute power (dBm) or in relation to carrier power (dBc) (13).

FORMULA 1. Formulas that describes the frequencies of IM products

$f_{IM(M+N)\ low} = M * f_1 \pm N * \ f_2$

$f_{IM(M+N)\ high} = M * f_2 \pm N * f_1$

Where

$M = \text{integer} \geq 2$

$N = M - 1$

$f_{IM(M+N)\,low}\,, f_{IM(M+N)high} = \text{odd order IM frequencies}$

$f_1, f_2 = \text{frequency of the tone input signals}$

This means that the *M* value for IM_3 equation is 2 and *N* value is 1. The same principle applies to IM_5 where *M* = 3 and *N* = 2. Two formulas are needed because in a two-tone scenario IM products are generated on a frequency that is below the first tone ($f_{IM\ low}$) and on a frequency after the second tone ($f_{IM\ high}$).

An intermodulation intercept point is a measure of linearity of an RF device and it is used to describe the performance of a component or a device. In this point the IM product has grown to the same level as the original signal at the output side of the DUT. It is a purely mathematical concept because the point is usually far beyond the breaking point of the DUT. The third order intercept point (IP3) is typically calculated because, as mentioned earlier, IM3 products have the highest level and are closest to the original signals (FIGURE 6).

As the level of tones rise, so does the level of IM products. It is found that the level of IM products rise faster than that of the tone in the DUT output. The higher the order, the faster they rise. It can be thought that a 1 dB rise in the tone level raises the level of IM3 products by 3 dB and the level of IM5 products by 5 dB. All IM products can be plotted and the intercept point (IP) can be extrapolated. A higher IP means a better performance (14). The intermodulation intercept point can be calculated from IM measurement results. The odd order IP can be modeled using a low-order polynomial, derived by means of Taylor series (13).

FORMULA 2. Formula for calculating intercept point (13)

$IP_n = P_{tone} + P_{\Delta}/2$

Where

$IP_n =$ nth order intercept point

P_{tone} = power level of input signal

P_{Δ} = power level - IM_n level

Interception point can be illustrated graphically with the Cartesian coordinate system where a vertical axis is the output level in dBm and a horizontal axis is input level in dBm. Theoretical lines of the tone and IM3 product are plotted and the point where the lines cross is the intercept point for the third harmonics (IP3). The output intercept point (OIP3) power level for IP3 can be read from the vertical axis and the input intercept point (IIP3) power level from the horizontal axis (FIGURE 7). IIP3 is a design parameter typically used for RF receivers and OIP3 is a design parameter for RF transmitters.

Intercept points are extrapolated from the data measured on lower signals levels because they are not directly measureable. Their accuracy is based on the assumption that the curves of IM3 products are described by straight lines with a slope of three (14).

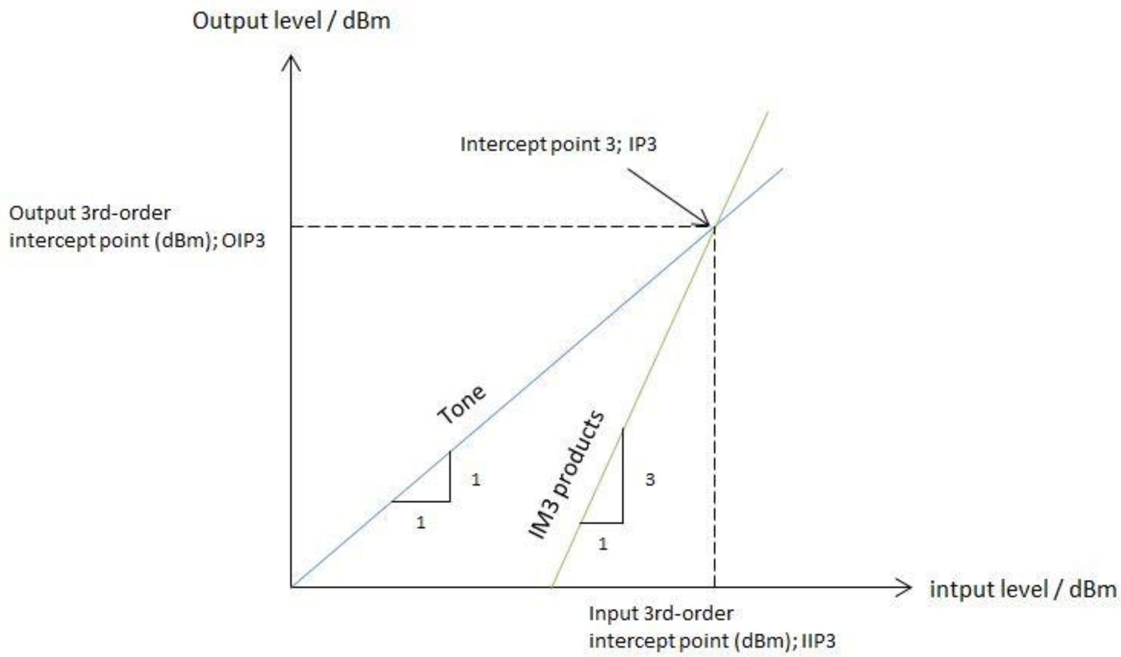

FIGURE 7. Third order intercept point

3 PIM MEASUREMENT SETUP

A measurement setup was built for two-tone PIM measurements. Highly linear components were selected to a measurement setup in order to minimize the nonlinearities generated by the setup. The measurement setup is very flexible so that various frequency bands can be measured. Commercial PIM test equipment is available but the price of this kind of systems is often multiple times higher than the price of a built system. Commercial alternatives may have a better performance but a test system built based on off the shelf equipment can easily be optimized. A calibration of the self-built system needs to be done carefully.

A measurement system with a high dynamic range is needed in order to perform PIM measurements. The high dynamic range is an important specification when measuring low-power signals, like IM products, which are close in frequency domain to high-power signals. The dynamic range of the measurement instrument defines the power of the minimum signals so that it can view next to a high-power signal because the reference level of the instrument cannot be set below the maximum power of the highest power signal (15).

3.1 Overview

Commercial PIM testers are available but they are often targeted to measure end products. A self-built system is more suited for testing individual components. The testing time of the final product can be reduced when the PIM performance of components is studied and tested during the research and development phase. PIM measurements are carried out in different conditions like changing the measurement temperature or altering signal fequencies and power levels. The PIM measurement setup built for this thesis is shown in FIGURE 8. It includes the following equipment:

- Two low noise RF signal generators
- Multiple laboratory RF circulators
- Two highly linear RF laboratory amplifiers

- A 2-way RF power combiner
- Multiple tunable laboratory notch filters
- A Temperature chamber
- An RF spectrum analyzer

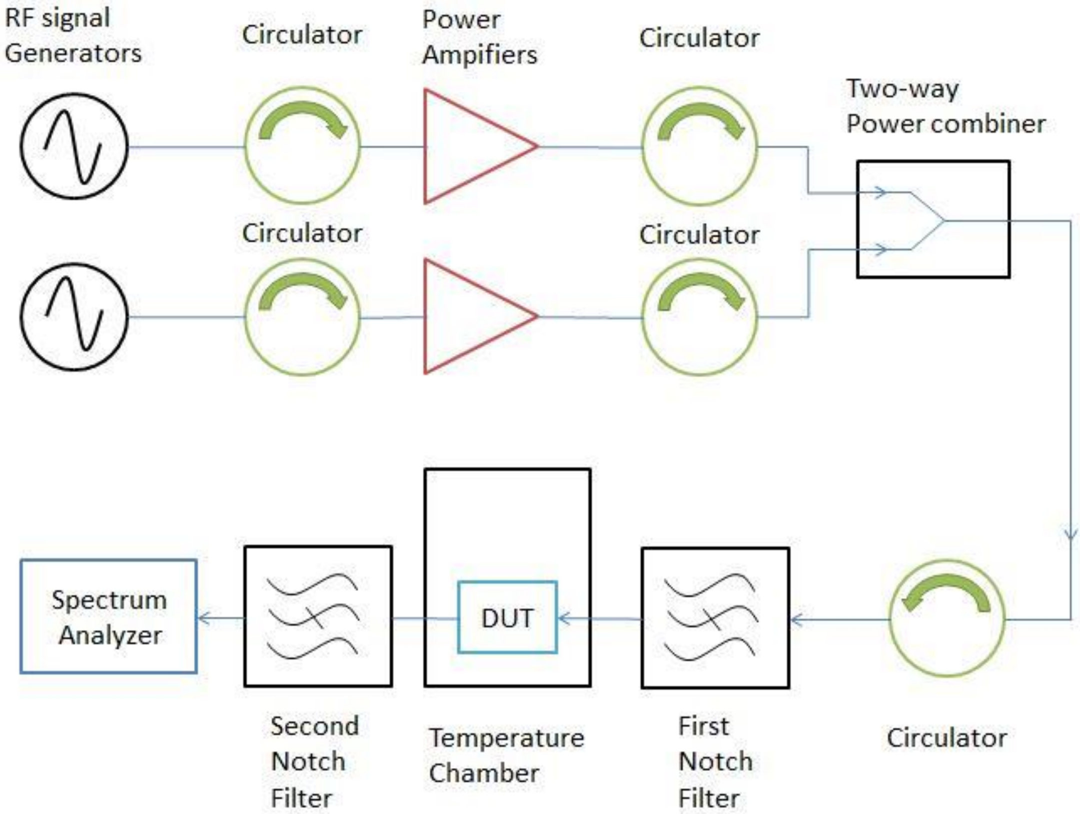

FIGURE 8. Block diagram of the built measurement setup

Each of used equipment will be described more in detail in following chapters like main function, linearity of the device and possible impact on the measurement performance.

3.1.1 RF signal generators

RF signal generators are used to create the test tones and each tone requires its own signal generator. An RF vector signal generator is capable of generating multiple test signals but an RF vector signal generator was not available for the test system.

Low noise RF signal generators with the frequency range of 10 kHz – 5.4 GHz and the maximum output power of +13 dBm were used as test signal sources. Generators have a good linearity with harmonic levels better than -90 dBc at RF level up to +7 dBm on frequencies from 20 MHz – 2.7 GHz (16).

Signal generators were used at RF levels below -5 dBm because the desired level for individual tone is +26 dBm, and generators can only output the maximum of +13 dBm. Hence, a power amplifier was needed.

3.1.2 RF Circulators

Circulators are passive components which are used to protect RF equipment from reflected RF signals which are entering to the input of the equipment. Reflected RF signals may have been caused by a mismatched load of the following device in the signal path. The way circulators are used in the measurement setup is shown in FIGURE 9. A signal is fed into the port 1 and it comes out from the port 2.

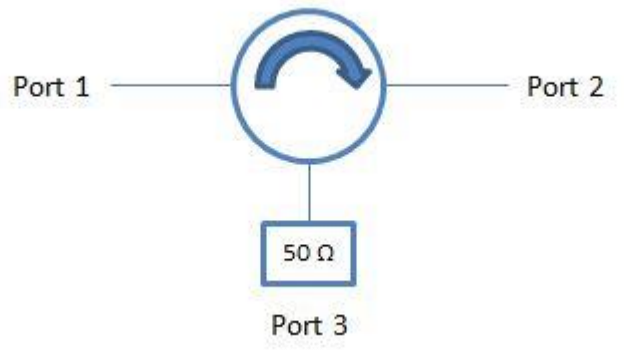

FIGURE 9. Three port clockwise circulator with terminated third port

A circulator is the next component in the signal path after RF signal generators. A circulator is typically a 3-port device, which allows a signal flow to only one direction. A circulator may be done to circulate signals either clockwise or counterclockwise. Circulation direction does not serve any practical purpose in this setup and both types could have been used. In the measurement setup a third port of each circulator is always terminated with 50 Ω load, as shown in FIGURE 9, in order to provide the needed isolation. In this particular case circulators could have been replaced with isolators but none were available at the time of measurements.

An insertion loss (IL) from the port 1 to the port 2 is typically fairly low. The measured insertion loss for the used circulators varied from 0.19 dB to 0.30 dB and the average IL value was 0.21 dB at all the frequencies used for measurements. A minimum return loss (RL) for the worst performing circulator was 19 dB and the average RL for all the circulators was 25 dB. A return loss describes how many decibels signals going against the circulation direction are going to be attenuated.

3.1.3 Laboratory RF power amplifiers

After the signal generator and circulator, the next component is a laboratory RF power amplifier (PA) which is used to amplify the output signal of the generator in order to achieve a +26 dBm tone level at the input port of the DUT. It has a gain value in dB that describes how much the input signal of the PA is going to be amplified. The output signal level of the PA is roughly the input level (dBm) + PA gain. Things like the used supply voltage and the frequency of the input signal can affect the gain of the PA to some degree but these effects are usually described in the datasheet (17).

An amplifier is an active component meaning that it needs an external source for a supply voltage to operate. +15V DC was used as a supply voltage for the laboratory RF power amplifier. A power amplifier is a nonlinear component but the used laboratory PAs were linear enough, not affecting the measurement results of the DUT.

3.1.4 Two-way RF power combiner

A two-way RF power combiner has two input ports and one output port. A two-way power combiner can be used to split one signal into two separate signals or to combine two separate signals into one. A two-way combiner was used to combine the two test signals in the measurement setup which were created by the RF signal generators and then amplified by the Laboratory RF power amplifiers. Individual test signals are applied to the ports 1 and 2 of the two-way combiner and one multitone signal comes out from the port 3 (FIGURE 10).

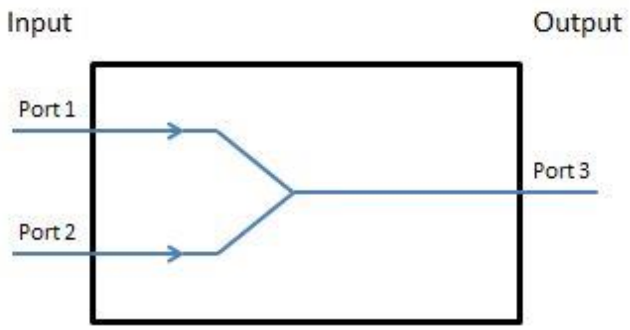

FIGURE 10. Basic two-way power combiner

A maximum measured insertion loss from the input to the output port was 3.25 dB covering the frequency range that was used for measurements. A high isolation between input ports 1 and 2 is preferred since it prevents signals to leak from the input port 1 to the input port 2 and vice versa. The signals leaking between the input ports may reflect back and damage components that are before the combiner. The lowest measured isolation between the input ports of a two-way power combiner was 25 dB, which was a good enough isolation value.

3.1.5 Tunable laboratory notch filters

Tunable laboratory notch filters have a tunable stop band, which may be tuned to test signal tone frequency or IM product frequencies in order to improve the dynamic range of the measurement setup. A first notch filter was placed before the DUT and it is tuned so that two stop bands are created on IM3 product frequencies calculated with FORMULA 1. The purpose of the first notch filter is to attenuate the nonlinear components produced by the measurement setup.

A second notch filter was placed after the DUT and stop bands were tuned to test signal tone frequencies in order to further improve the dynamic range and thus the capability of the RF Spectrum analyzer to measure IM products. As the test signal absolute level at DUT's output port is not of interest when measuring IM3 products, they can be filtered out. Notch filters were manually tuned with a network analyzer and a 24 – 28 dB attenuation was achieved for all stop bands.

3.1.6 RF Spectrum analyzer

A spectrum analyzer is a measurement instrument which is used to measure and visualize the two tone signal at the output port of the DUT. A spectrum analyzer is required when looking at complex signals or cases where multiple signals are present.

A spectrum analyzer includes RF components which are nonlinear hence making the whole device nonlinear. The main contributor to linearity of the spectrum analyzer is the first input mixer. The IM products of the first input mixer start dominating the total spectrum analyzer IMD performance at certain levels that are typically specified in the datasheet of the measurement equipment. IM caused by the mixer can be lowered by reducing the input level or using an input step attenuator. An input attenuator is a linear passive component and all modern analyzers are equipped with one (13).

The instrument itself has a few factors that affect IM measurements and one of them is a noise floor level. The noise floor provides an indication of the smallest signal that the instrument can display. Thus signals, which fall below it will not be measurable (15). The settings of a spectrum analyzer, which can be used to lower the noise floor and which have an impact on the measurements, are described in more detail in chapter 4.2.

3.2 Measurement setup calibration

The measurement setup calibration consists of a test signal level calibration to the input port of the DUT and a post-DUT attenuation calibration. The level of test signal at DUT’s input could be calculated when the transmitted signal level and losses and gains in the setup are known but it is a quite time consuming task when the setup has several components. In addition, a small signal gain of the system is frequency dependent and that further complicates the calculations.

A faster and easier way to calibrate the setup than calculating is to replace the DUT with a through connector. First the insertion loss of the second notch filter and the attenuation of the RF cables that are after DUT have to be calibrated using a network analyzer. The reference level offset value of a spectrum analyzer is set equal to the total post-DUT cable attenuation at IM3 frequencies. The measured attenuation for two RF cables was on average 2.1 dB over the measurement frequency range. The effect of cables is calibrated away by setting a reference level offset, and signals at the DUT output port can be accurately measured.

After post-DUT losses have been calibrated, the output levels of test signals from generators can be calibrated. The second notch filter, which is shown in FIGURE 8, should be removed for the duration of generator output calibration because it is necessary to measure tone levels. The output level of generator is set to a low level in the beginning so that the correct operation of the setup can be verified. This also ensures that the maximum RF input level for power amplifiers and a spectrum analyzer is not exceeded.

If the setup is working correctly, the generator output can be raised until the desired tone level is achieved. Measurements are done as a power sweep meaning that multiple tone levels are, used and corresponding IM3 product levels are measured. It is necessary to calibrate every sweep step because, especially on higher signal levels, a 1 dB rise in the generator output does not correspond to a 1dB rise in the input of the DUT.

Both test signal paths need to be calibrated separately because even though the RF signal generators and laboratory RF power amplifiers are of the same model, they can still perform slightly differently.

3.3 Measurement setup analysis

Sufficient sensitivity for the measurement setup was achieved with filtering out the tone signals. A maximum dynamic range of -120 dBc was obtained. IM3 products generated by the DUT with a power level of -120 dBc could be reliably measured at the lower power level of the power sweep. A minimum dynamic range for the measurement system without DUT was -84 dBc. IM3 levels generated by the system were more than -84 dBc at the highest power level of the power sweep on every frequency that was used for measurements (FIGURE

11). An average IM3 level generated by the system was below -90 dBc at the four highest sweep levels.

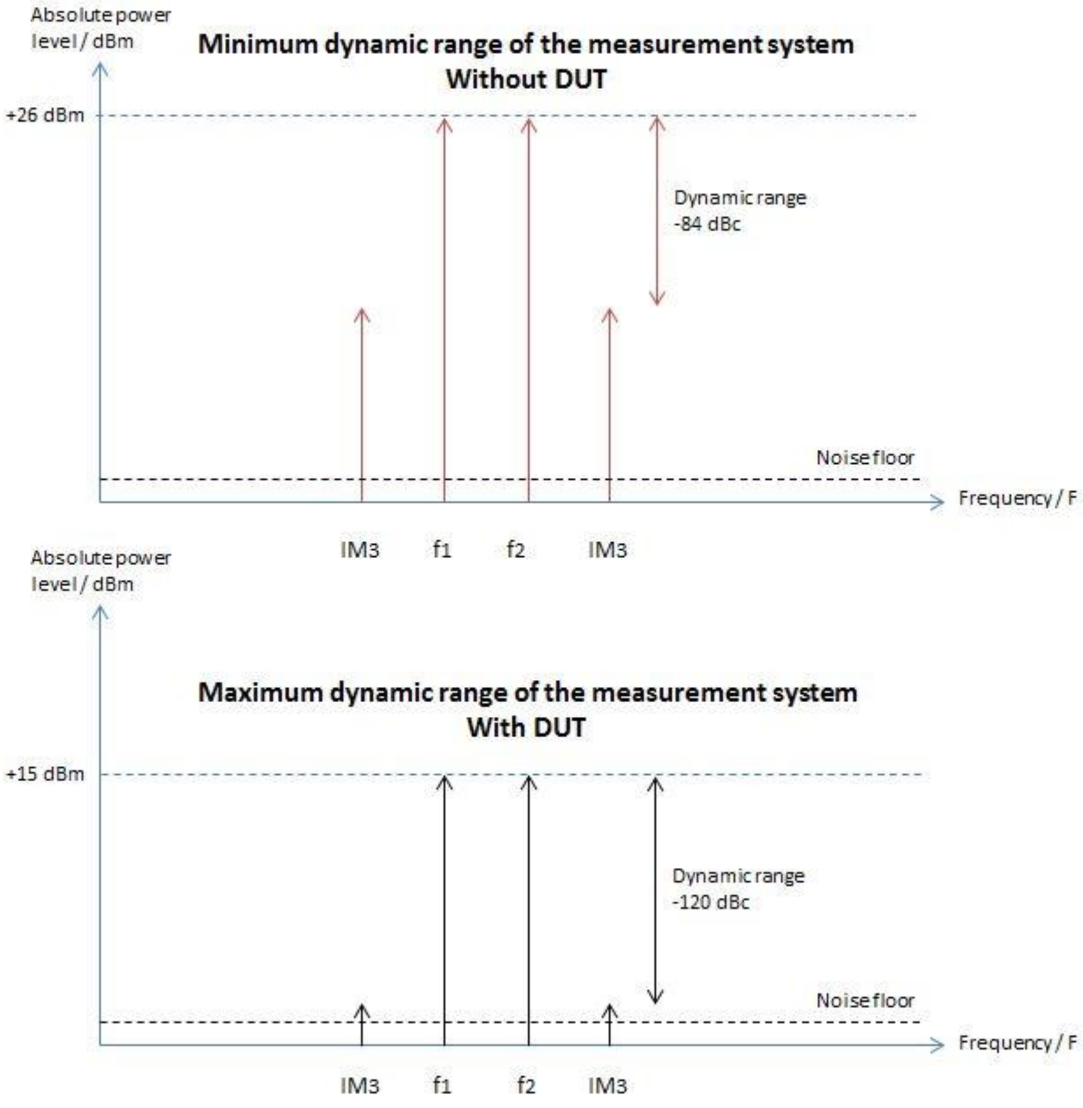

FIGURE 11. Measured minimum and maximum dynamic ranges

Currently, the system cannot have any more losses after laboratory PAs because they operate at the 1 dB compression point which is the input level that causes the gain to drop 1 dB from the specified normal linear gain. At this point a further increase in input power does not increase output power. It is also the point when the PA becomes saturated and its response becomes significantly nonlinear. It may also create IM products and cause distortion (18). A specified minimum output power at the 1 dB compression point for the laboratory PAs was +28 dBm (17) when the desired input level for the DUT is +26 dBm. In order to operate the laboratory PA in a linear range, a maximum theoretical loss between the output of the laboratory PA and the input of the DUT can only be about 2 dB. The measured loss for above-mentioned path was 5.9 dB. Hence, a conclusion can be made that the laboratory PA is operating in a nonlinear range, but it is linear enough for testing purposes.

When measuring with a 60 MHz tone spacing, it was noted that when the mechanical attenuation value of the spectrum analyzer exceeded a certain point, the IM3 product level changed notably. A 1 dB change in attenuation could change the IM3 level by 5-10 dB, which led to a conclusion that one of the many filters inside the spectrum analyser was filtering IM3 products away. After this observation, measurements were conducted with a mechanical attenuation level that showed the highest IM3 levels because they are likely to be the real values.

A good measurement repeatability was achieved meaning that under the same measurement conditions results were almost the same every time. It was noted that the power level of small IM signals always fluctuated to some degree and the typical fluctuation was within ±1 dB between measurements. The measurement repeatability is a good indication that the setup is working as intended and if the results differ drastically for one of the devices under test, in most cases the fault is in the DUT.

A poor connection in the output port of one of the devices under test was spotted when re-test results differed significantly from the previous test results. A poorly performing DUT was checked with a network analyzer and it was noticed that slightly moving the output port connector increased the insertion loss by almost 20 dB. A solder was added to the before mentioned port in order to establish a better connection. After soldering the component was re-measured again with the network analyzer and based on the measurement results the component was performing as expected.

During the measurements, it was noticed that some of the used RF cables had a significant effect on IM results. When broken cables were moved or even touched a little, the measured IM level fluctuated several decibels. Poor cables were replaced by well performing cables and the measurements that had been done using the poor cables were redone.

4 CONDUCTING PIM MEASUREMENTS

Passive intermodulation measurements were done using two test signal tones and a power sweep was performed for all the different measurements. It is important to perform a power sweep because the level of PIM results may have a power dependency or it may vary based on input power levels (11). Three different tone spacings and three different measurement temperatures were used. The used bandwidths for tone spacing were 20, 40 and 60 MHz. Tone spacing emulates multiple LTE signal bandwidths, which may be used at the same time on the same frequency band. The devices under test are tested at various temperatures because it cannot be said for certainty what the operation temperature of the filter will be inside the end product. The end product is specified to work on a range of temperatures and all the components inside it must have specifications for these conditions, too.

After the measurement setup was built, test specifications for the DUTs were defined. The specification included things like a power sweep range, test tone frequencies and spacing, a temperature range and which harmonic frequencies are to be measured. The second and third harmonics were measured but they will not be discussed in detail in this thesis. A Microsoft Excel worksheet was made based on the test specifications for each DUT.

It was noticed that multiple things can affect the quality of measurements, e.g. the settings of spectrum analyzer and setup calibration. All these things have to be optimized for each DUT in order to obtain reliable results.

4.1 Measured filters and measurement specifications

Both the SAW and BAW type of TDD filters were measured from three filter manufacturers and in total of nine different TDD filters were measured. Component manufacturers and specific component names are not mentioned due to a non-disclosure agreement. Measured filters were specified for three different 3GPP TDD bands. Measured filters had different bandwidths and center frequencies for pass bands, which meant that common test tone frequencies could not be used for components that operate on the same band.

Test tones were spaced around the center frequency of the band. In seven cases the narrowest tone spacing generated the IM3 products that were within the specified pass band and in two of them the IM3 products were a couple of MHz outside the specified pass band. The other two tone spacings only produced IM3 products on the pass band for the components with the widest pass band.

Otherwise, the same measurement specifications were used for all the components. The used signal levels for a power sweep ranged from +15 dBm to +26 dBm for each test tone and the same sweep was used for all the different spacings. The used temperature conditions were low (-30 °C), room (+25 °C) and high (+85 °C) temperature.

Measurement results were logged to the Excel worksheet and measurements were conducted once. A power sweep was performed from the highest signal level to the lowest. Once the sweep was complete, a signal level was set back to the highest level and IM3 product results were checked again but not logged. If the results were within 0.5 dB of each other, a correct operation of the measurement setup and DUT could be verified based on the measurement repeatability described in chapter 3.3.

Each measurement equipment was operated manually. The measurement process itself could be automated but a development of automated test control software was not feasible during the thesis. Automated test software would speed-up future measurements but the calibration of the measurement system and the tuning of the laboratory notch filters always needs to be done manually because it requires that some of the components are removed for the duration of the calibration as described in chapter 3.2. Thus, a feasibility and level of atomisation of PIM testing should be analysed carefully.

4.2 Settings of spectrum analyzer and their effect on measurements

A spectrum analyzer has a couple of settings than can be changed in order to measure low power signals more accurately. The settings that were controlled manually and used to optimize the measurements were a frequency span, a resolution bandwidth (RBW), a video bandwidth (VBW), a noise cancellation, a mechanical attenuation and a sweep optimization. A sweep time can also affect measurements but this setting was kept on auto, meaning that the measurement instrument will control it.

4.2.1 Frequency span

A frequency span defines the frequency range that is displayed on the LCD screen of the spectrum analyzer. If the span is too narrow, IM3 products will not be visible on the screen and hence cannot be measured. A too wide span makes it difficult to separate the tones and IMs from each other. A typical span that was used for measurements was four times the spacing of the tones. This ensured that the IM3 products are clearly visible and not at the edge of the screen. The span setting does not affect absolute signal levels at all nor does it affect the noise floor of the spectrum analyzer (20).

4.2.2 Resolution bandwidth

A resolution bandwidth is a setting that is used when viewing multiple signals that are close to each other in the frequency domain. It is a pass band filter which determines how well closely spaced signals can be separated (19). A narrow RBW was used for measurements in order to clearly separate the signals and to improve the sensitivity of the measurement equipment. Like a frequency span, RBW does not have any effect on signals levels but it lowers the noise floor of the spectrum analyzer. Narrowing the RBW increases the sweep time of the instrument but a longer sweep time was not an issue for these measurements.

4.2.3 Sweep time

A sweep time defines the duration of a single sweep, during which the defined number of sweep points are measured. The settings that affect the sweep time are a frequency span, RBW and VBW. Decreasing a span reduces the sweep time and decreasing an RBW and VBW filter bandwidth increases the sweep time. These filters have a settling time that must be awaited in order to obtain correct results. The smaller of these two determines the minimum sweep time required for the measurements. A level measurement error will occur if the selected sweep time is too short for the selected filter bandwidth and frequency span. For the component measurements, the sweep time was set to auto. The measurement instrument will adjust the sweep time accordingly if a span or filter bandwidths are changed ensuring that the sweep time is long enough (20).

4.2.4 Video bandwidth

A video bandwidth is a low pass filter that is used to smoothen the displayed trace. It improves the resolution of very weak signals in the presence of the noise signal. A video bandwidth does not lower the noise floor of the instrument but it improves the discernibility and repeatability of low signal-to-noise ratio measurements. It only reduces noise on the trace (19). VBW works by displaying the signal average thus repressing noise peaks and pulse signals. This filter is located just before the screen display inside the instrument so it does not influence the absolute level of a sine wave signal. Small VBW compared to RBW is used to free the sine wave signal from noise and this makes it so that they can be measured more accurately (20).

4.2.5 Noise cancellation

A spectrum analyzer has a noise cancellation option, which will improve the dynamic range of the instrument when it is turned on. When a noise cancellation is used, a reference measurement of inherent noise of the instrument is carried out. The measured noise power is then subtracted from the power in the channel that is being analyzed. Few settings affect the inherent noise of the instruments and these settings are a selected center frequency, RBW and a level setting. If one of these settings is changed, the correction function should be turned off. Once the settings are changed, the correction function can be turned on again and a new reference measurement is carried out (20).

However, the noise cancellation function was not used correctly during the measurements. It was not realized that the function is not constantly running the reference measurements and thus reducing noise constantly. Some measurements took place before the writing of the thesis began and the correct operation of this function was not used correctly. In order to avoid redoing all measurements the noise cancellation was left out from measurements results. In this way the old and new results are comparable because the noise cancellation was not used for any measurement. In hindsight the correct use of noise cancellation most likely would not have improved the measurement results much if at all because the intermodulation products were clearly above the noise floor of the spectrum analyzer.

4.2.6 RF attenuation

The signals at the RF input of the spectrum analyzer can be attenuated with an RF attenuation setting before they enter the first mixer. This RF attenuator can be either mechanical or electrical. A mechanical attenuator was used during the measurements because an electrical attenuator was not installed on the spectrum analyzer. An RF attenuator is used to prevent overload at the RF input. Overload can happen if the signal at the input exceeds the maximum allowed level (20). In this measurement system there is no risk that the signal level at the input is too high if the second laboratory RF notch filter is tuned correctly to test tone frequencies. A theoretical maximum total power level at the input of the instrument is around +27 dBm if the test tone frequencies do not match the stop bands of the second notch filter, the maximum allowed input level being +30 dBm.

Increase in the mechanical attenuation level increases the noise floor of the instrument thus directly reducing its sensitivity. The highest sensitivity is obtained when the RF attenuation is set to 0 dB and in this it was mainly used for the measurements. Each additional 10 dB step reduces the sensitivity by 10 dB (20). During the test tone level calibration RF attenuation levels between 20 – 30 dB should be used because otherwise the reference level of the instrument cannot be set to a level where tones are fully visible on the display. Reduced sensitivity does not affect the calibration and it is more important to protect the measurement instrument from high power levels.

Before starting any future measurements, it might be worthwhile to clarify why IM products are sometimes heavily attenuated under certain conditions, described in chapter 3.3, when the RF attenuation level is changed.

5 ANALYSIS OF THE RESULTS

An analysis of the results was carried out when all the measurements had been done and the results were logged to the Excel files. Each test tone spacing had its own sheet in the Excel file and IM3 signals levels in every used measurement temperature were logged to these sheets. In this way the effect of the temperature variation in relation to the tone spacing could be easily analyzed. Intermodulation products in this thesis are referred as “IM low” and “IM high” as shown in FIGURE 6. IM low is the product that is at frequency $2 * f_1 - f_2$ and IM high is at frequency $2 * f_2 - f_1$. Each sheet had results for six power sweeps, IM low and IM high sweep for three different temperatures. All the six power sweeps were plotted to one scatter chart. Charts show the IM product absolute power level as a function of power of a single CW tone as seen in FIGURE 12.

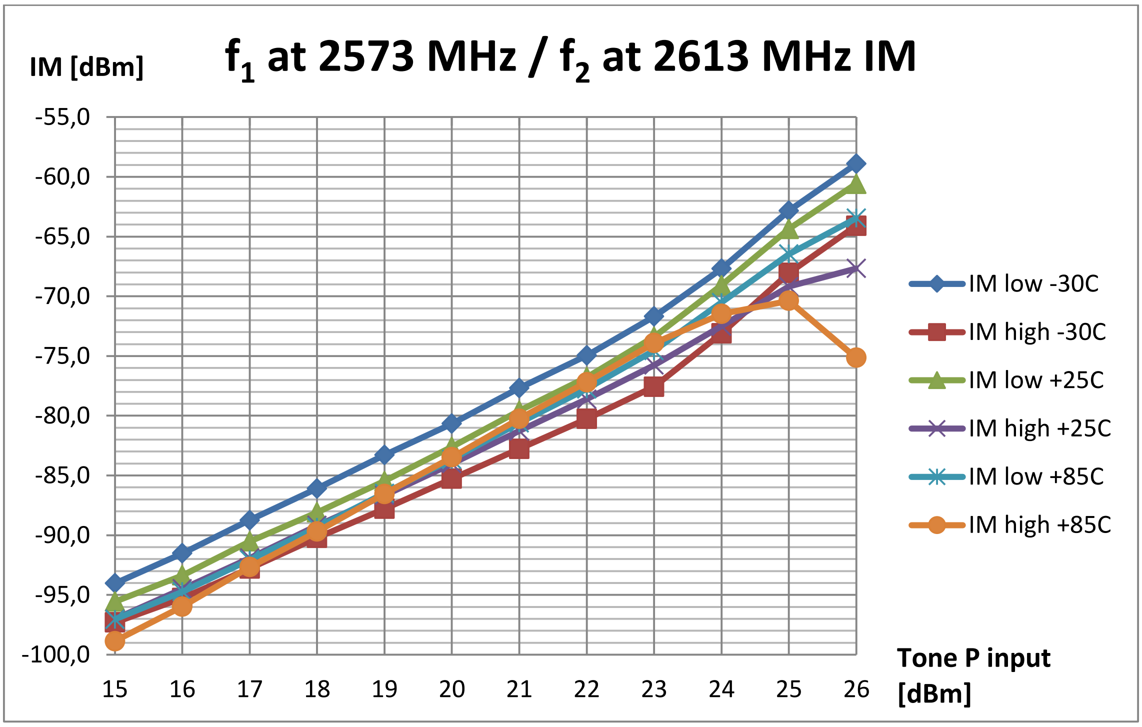

FIGURE 12. Summary of 40 MHz spacing from one of the DUTs

The results show that the IM3 levels are not only dependent on the used tone spacing and frequency. The input signal level also affects the results. It was observed that certain input levels and frequencies can produce IM levels that are much higher or lower than if they would follow the previous measurements of the theory. Such phenomenon can be seen in FIGURE 12 on “IM high +85C” measurement. Results from +15 dBm to +24 dBm are well in line with each other but the last two sweep levels differ from the rest. The second last sweep point is only 1.1 dBm higher than the previous point and the IM level on the last sweep point is almost 5 dBm lower than the second last result. Similar kinds of notches in measurement results were seen on few other DUTs, too. Most probably this phenomenon has been caused by a destructive summation of IM products inside the filter structure.

The main point of the analysis was to find out if the IM products follow a theoretical third order model where 1 dB rise in a test tone level raises the level of IM3 products by 3 dB. This phenomenon was studied with a trend line analysis. For each set of measurements a trend line was fitted to the results, when test tone and measurement results were presented on a logarithmic scale. The trend line was fitted to measurement results by using a least squares fitting method. It is a mathematical procedure which is used to find the best-fitting curve to a given set of points by minimizing the sum of the squares of the offsets of the points from the curve (21). The trend line is a linear function and it is described in FORMULA 3.

FORMULA 3. Linear trend line equation (22)

$$f(x) = ax + b$$

where

a = slope

b = constant

The slope is a number that show how steeply the line is slanted. A greater number means that the line is slanted more steeply. The constant value *b* describes the intersection point with the *y*-axis for the line (22). Y-axis intersection point is not relevant in this case thus only the slope is examined. Another value that is displayed together with the trend line is coefficient of determination, denoted R^2. It is a value that is used to indicate how well the measured data fits a statistic model which in this case is the trend line. R^2 is a value which varies between 0 to 1 and a higher value means that the regression line fits the data more accurately (23). If the R^2 value is greater than 0.90, the line fit can be consider to be very good. If the R^2 value is between 0.90 and 0.60, then the line fit can be considered reasonably good. The R^2 value below 0.60 is considered poor. A trend line was added to the power sweeps shown in FIGURE 12 and the trend line equation and R^2 value for it are shown in FIGURE 13. Displayed equations are colored with corresponding IM product colors that are shown in FIGURE 13 legend.

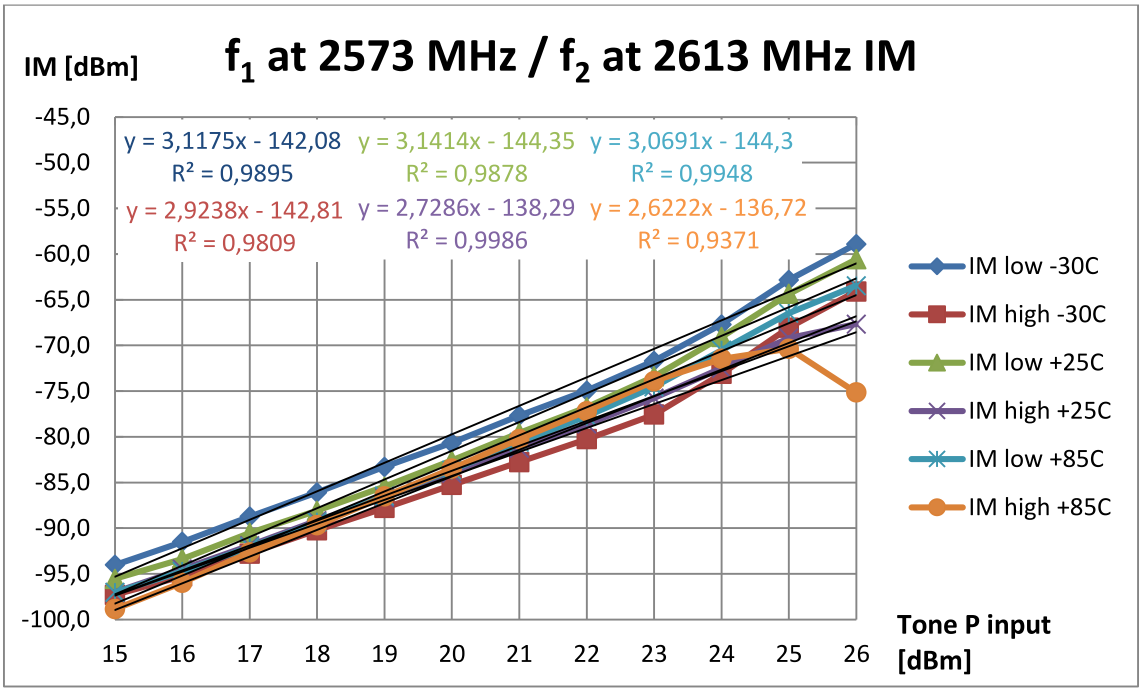

FIGURE 13. Summary of 40 MHz spacing with trend line and R^2 value displayed

It can be seen in FIGURE 13 that the temperature only has a minor impact on the results. Slopes are quite well in line with the third order intermodulation theory, 2.6 being the lowest and 3.1 being the highest slope value. All R^2 values, expect one where a steep notch can be seen, are above 0.98, which means that the regression lines fit to the data almost perfectly.

5.1 Overall results

The previous chapter showed an example of a single DUT result analysis. In this chapter the overall results for all nine DUTs are analyzed. Variables such as tone spacing, temperature and IM product frequency (low side and high side) and their impact on the power sweep slopes are analyzed in chapters 5.1.1 – 5.1.3. In total the data has 156 slope values because one of the DUTs was not measured with a 60 MHz tone spacing due to a narrow pass band of the DUT. The power sweep slope and R^2 values were analyzed using Minitab software. An average slope value for all power sweeps was 2.88 and a standard deviation for the slope was 0.28 (FIGURE 14) meaning that one dB drop in the input signal level corresponds to a 2.88 dB drop in IM3 signal levels. Based on the outcome of the measurements, they seem to follow the theory well. In this case the difference between the theory and the measured results is less than 10 % which is a good result. It can be said that the IM3 products of these filters follow the third order intermodulation theory.

An average coefficient of determination (R^2) for the same set of data was 0.99 with a standard deviation of 0.01 (FIGURE 15). Based on this, it can be concluded that the measurement results fitted well to the third order modulation equation.

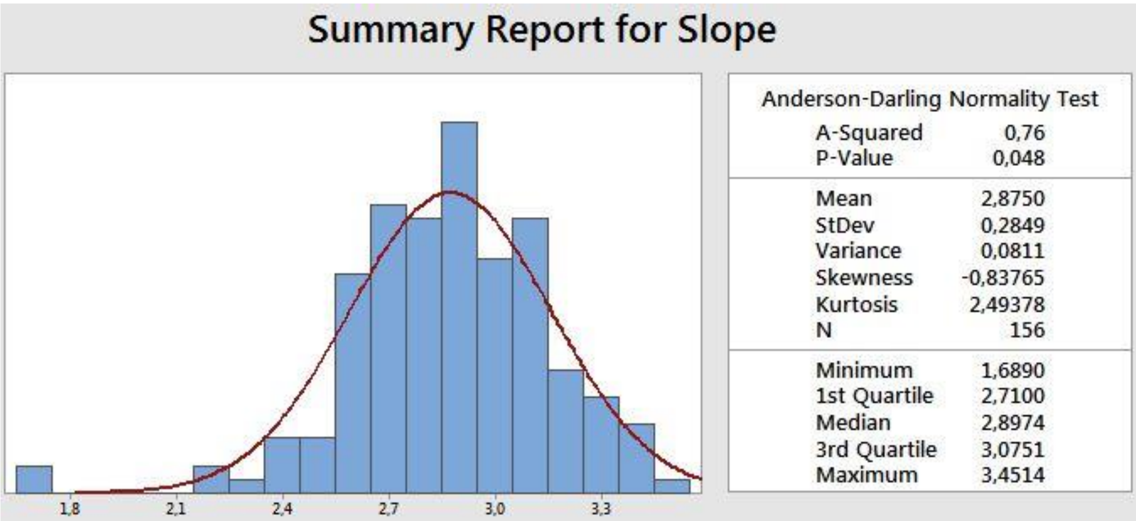

FIGURE 14. Average slope value for all power sweeps

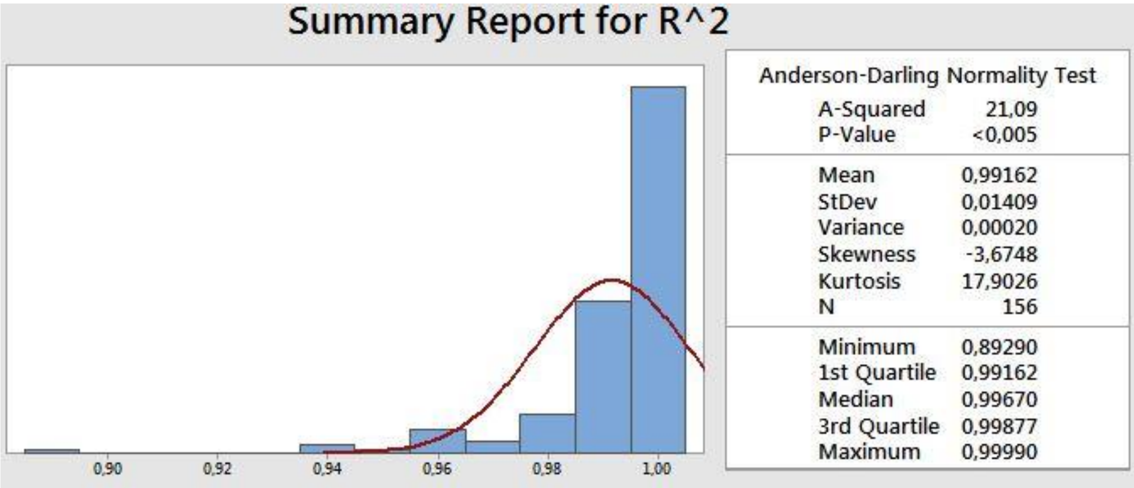

FIGURE 15. Average R^2 value for all power sweeps

5.1.1 Tone spacing effect on slope

In this chapter the average of slope values are analyzed as a function of tone spacing. As mentioned before, three different test tone spacings (20, 40 and 60 MHz) were used during the measurements. PIM effects of the component can be more accurately characterized when multiple tone spacings are used. Intermodulation products that are on the rejection band should drop as much as the IM products that are on the pass band and the only difference is the initial absolute IM product level. Filters that have very steep pass band skirts might create notch spots at skirt frequencies. This may cause the IM3 products levels to drop slower or faster, thus deviating the measured slope value. If a filter’s skirt is gentle enough, notch spots might not be manifested, but in the end this is component specific.

The average slope value for all the 20 and 40 MHz spacing measurements was almost exactly the same, being 2.94 for 20 MHz spacing and 2.91 for 40 MHz spacing. A standard deviation for 20 MHz spacing was 0.28 and for 40 MHz spacing 0.22.

60 MHz spacing had an average slope value of 2.76, which is somewhat lower than the other two spacings. It also had the biggest standard deviation value,

0.32. The reasons why the 60 MHz spacing differs from the other two are not clear and a further analysis would be needed in order to explain the physical root causes.

As a summary, 20 and 40 MHz spacing follow the theoretical slope ratio of 1:3 well and the obtained slope ratio for 60 MHz spacing was 1:2.75. Tone spacing did not have any significant effect on the coefficient of determination and R^2 value of 0.99 was obtained for each tone spacing.

5.1.2 Temperature effect on slope

In this chapter the average slope values are analyzed as a function of temperature. All three temperatures had slope values which were very close to each other. A low temperature had the steepest slope value of 2.90. A high temperature had the lowest slope value of 2.85 and a room temperature was between these two with a slope value of 2.87. The standard deviation for a low temperature was 0.29, for a room temperature 0.31 and for a high temperature 0.25. When results were analyzed as a function of temperature, the same R^2 value of 0.99 was obtained as for the tone spacing analysis. A small difference on the slope value over temperature is caused by the fact that the materials used for the filters perform better in lower than higher temperatures. But it is so marginal that it can be said that temperature does not have a significant impact on the power sweep slopes.

5.1.3 Intermodulation frequency effect on slope

In this chapter the average slope values are analyzed as a function of the IM frequency. A slight difference between the low side and high side slope values could be seen and a physical explanation behind this phenomenon is not obvious. A difference in low and high side levels was observed in 7 out of 9 DUTs. The low side was on average 0.1 – 0.5 dB higher in these cases and with the other 2 DUTs, where the high side was higher, the difference was only 0.1 dB on average if DUTs are compared individually.

When all the low side and high side results were put together and compared to each other, the low side had an average slope of 2.94 with a standard deviation of 0.32 and the high side had an average slope of 2.81 with a standard deviation of 0.22. The IM product frequency did not have an impact on the R^2 value, which was 0.99 for both sides.

As a summary, the lower IM3 product follows the theoretical slope ratio of 1:3 well and a 1:2.81 ratio was obtained for the higher IM3 product.

5.2 RF system level analysis of measurement results

An RF system level analysis was done for all the nine measured filters. This kind of analysis is done to analyze if a component can be used on an end product fulfilling the system requirements. An LTE communication system is standardized in the 3GPP. The 3GPP technical specification (TS) 36.104 specifies radio requirements for an LTE radio base station. This specification specifies, for example, the following important radio parameters: LTE frequency bands, conducted transmission power of base station and a spurious signal level for co-existence between different LTE bands.

Measured filters are indented to be used for small local area (LA) base stations. A manufacturer of the radio base station needs to declare available transmission power of the base station at the antenna connector. The document specifies that the maximum conducted output power of LA base stations can be $\leq$ + 24 dBm. The defined maximum spurious emission level for a co-existence requirement in the 3GPP specification is -88 dBm/100 kHz for an LA base station, which is co-located with another base station (24). In this analysis it is assumed that IM3 products will fall to an adjacent 3GPP operational frequency band.

One of the filters is analyzed as an example. If the 3rd order intermodulation product level is fixed to -88 dBm level in the output of the filter, then the input signal has to be dropped until the IM3 product levels are below the limit. Thus, the available output power for the base station is reduced since the input power level, when spurious signals (IM3 products) are below the maximum spurious emission level, is reduced. 20 MHz spacing results for one of the DUTs over temperatures are shown in FIGURE 16. It can be seen that the maximum rated output power for this filter with 20 MHz spacing could roughly be between +15.5 dBm and +18.5 dBm, which is lower than the maximum specified +24 dBm.

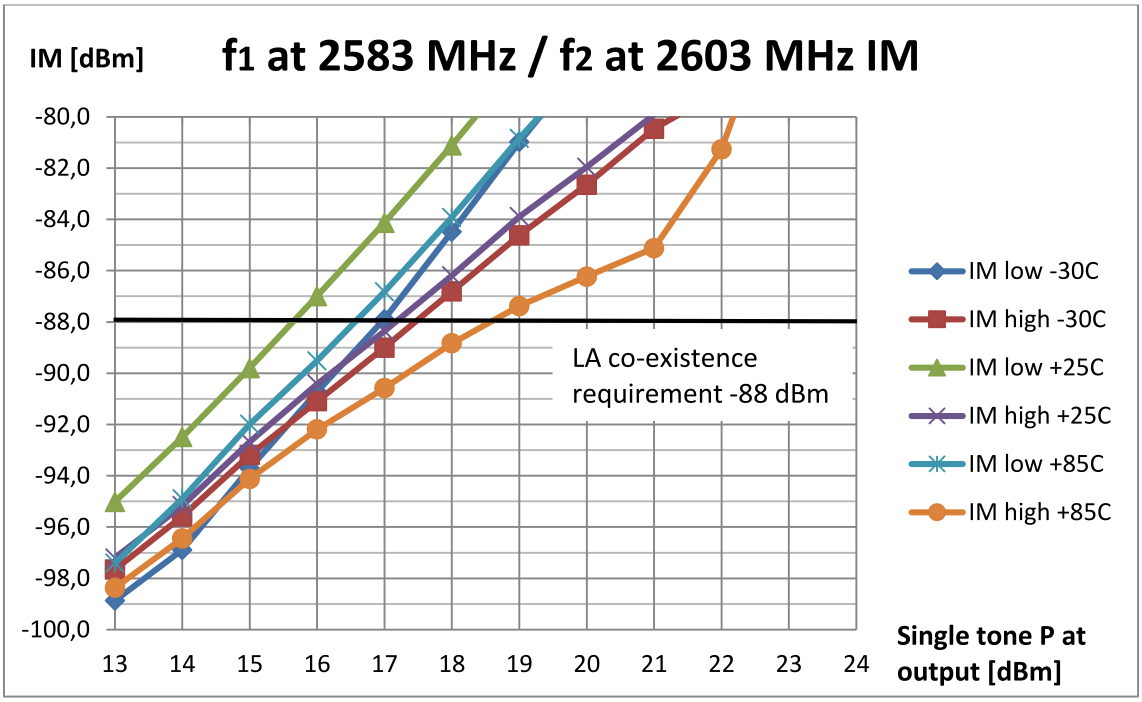

FIGURE 16. Summary of output IM level results for 20 MHz spacing for one of the DUTs

The same filter was analyzed from a single temperature behavior point of view for all three tone spacing and these results can be seen in FIGURE 17. Results are quite similar as in FIGURE 16. With this filter, the maximum rated output power over different test tone spacings would be roughly between +15.5 dBm and 17.5 dBm at +25 °C temperature. It can be seen that wider signal spacing improves the situation slightly.

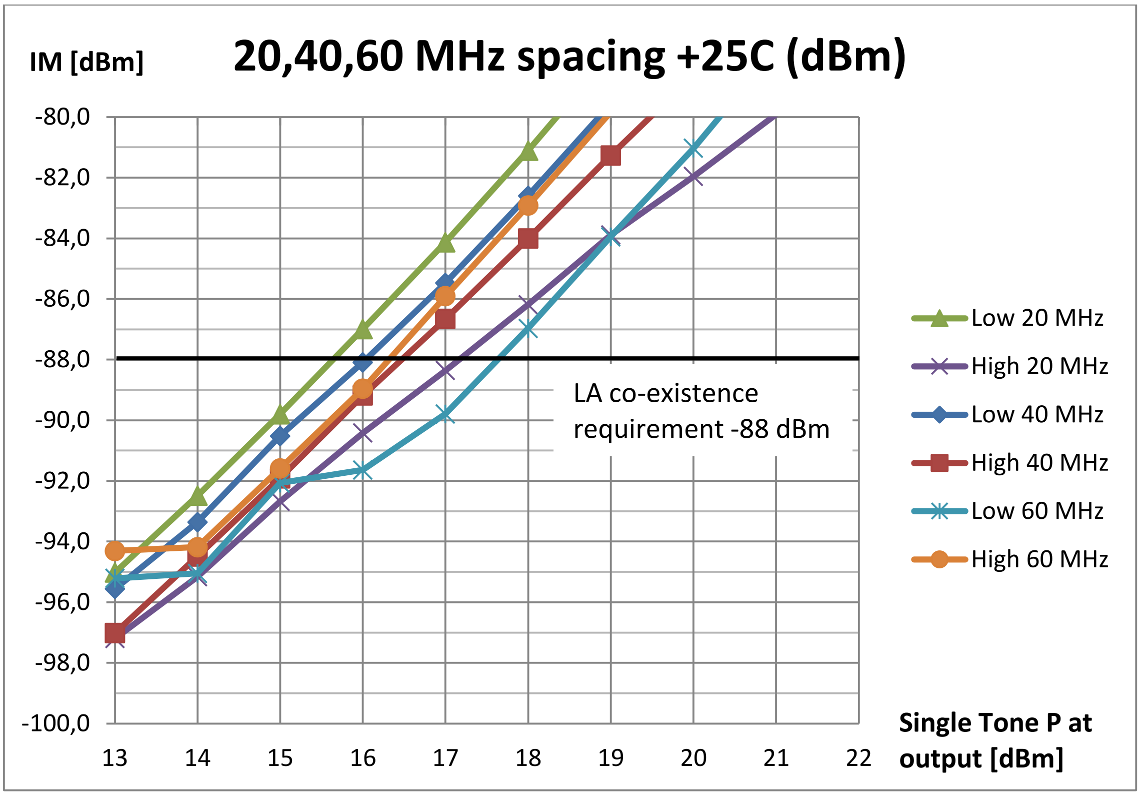

FIGURE 17. Summary of +25 °C temperature results over three bandwidths

If a CW measurement would fully correlate with a modulated LTE signal measurement, then based on the CW signal measurements none of the nine filters could operate at full +24 dBm local area output power. CW measurements are more stringent than the measurements done with a modulated signal, since with CW measurements all signal power is concentrated on a single frequency, while a modulated signal distributes the transmission power over a modulation signal bandwidth. Thus, CW signals can be considered to be the worst case scenario for IM measurements.

Additionally, different measurement and modulation bandwidths of the LTE signal will have an effect on the spurious signal performance. As an example, if a 20 MHz LTE signal is transmitted with a 24 dBm power level, then the spurious signal measurement bandwidth of 100 kHz would lower the signal by $10*(\log(18*10^6/100*10^3)=22.5$ dB. Thus, the measurement bandwidth would help with a modulated signal but not with a CW signal.

Absolute power levels on IM products with a CW signal at +24 dBm output power are between -56 and -76 dBm. The maximum output power for 20 MHz signal spacing that complies a spurious performance is between +13 and +15 dBm with single tone power and +16 to +18 dBm conducted power with two test tones. The results for 40 MHz signal spacing are almost the same since the maximum output would be between +15 and +16 dBm with single tone power and +18 to +19 dBm conducted power with two test tones. 60 MHz spacing differs a bit from the other two spacings. Some of the filters could operate at output levels of +18 to +19 dBm with single tone power but most of them could only operate at +13 to +15 dBm output levels with single tone power and +16 to +18 dBm conducted power with two test tones. Some of the measured filters did not fulfill the spurious requirements even at the lowest used power sweep input level, which was +15 dBm.

All output level results are for a single CW tone and since two tones were used, the total output power would be 3 dB higher than the results indicate. The output power, when a modulated signal is used, can be assumed to be the same as the two-tone output power level.

In conclusion, a CW tone measurement produces the worst case scenario spurious levels and might not represent the real life situation inside the end product. The PIM testing is needed to be carried out not only with CW but with a modulated signal as well in order to verify the PIM behavior.

6 CONCLUSION

The main objective of this thesis was to study a passive intermodulation distortion generated in nonlinear radio frequency filters. The first aim was to build a measurement setup with a high dynamic range so that intermodulation products can be reliably measured. The second aim was to compare obtained measurement results to theoretical passive intermodulation models and see how well the measured results correspond to 3rd order PIM models.

The subject of the thesis was interesting and challenging enough. It seemed pretty simple in the beginning but the more I read about it, the more I started to understand that PIM is a very complex phenomenon and not all underlying physical reasons are fully understood. The subject was limited to study radio frequency filters only in the thesis even though other RF components were measured during the thesis work.

A measurement setup with a high dynamic range was built in order to properly characterize the passive intermodulation distortion in RF filters. An existing measurement setup was modified for testing purposes.

Results were analyzed from several different points of view and in all cases they seem to support the 3rd order nonlinear model. It was found that 1 dB in input signal level corresponds to 3 dB drop in IM3 products like the theory suggests, since the measured slope ratio was 1:2.88 based on all the measurement results. Tone spacing was not found to make a difference to the slope ratio, since the ratio was 1:2.94 for 20 MHz tone spacing, 1:2.91 for 40 MHz tone spacing and 1:2.76 for 60 MHz tone spacing. Additionally, the measurement temperature had no effect on the slope ratio since the ratio was 1:2.90 for a low temperature, 1:2.87 for a room temperature and 1:2.85 for a high temperature. When the IM product frequency was studied, then the slope ratio was 1:2.94 for a lower IM3 product and 1:2.81 for a higher one.

The great coefficient of the determination value that was obtained assures that the measurement system was working correctly and that the measurements were executed accurately.

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APPENDICES

Appendix 1 Memo of initial data (in Finnish)

LÄHTÖTIETOMUISTIO

<table>
<tr><td rowspan="8">Työn tiedot</td><td>Tekijä[1]
Matias Pihlman</td><td>Tilaaja[2]
Oy LM Ericsson Ab</td></tr>
<tr><td colspan="2">Tilaajan yhdyshenkilö ja yhteystiedot[3]
Marko Leinonen [redacted]</td></tr>
<tr><td colspan="2">Työn nimi[4]
Passiivi-intermodulaatio radiotaajuus filttereissä</td></tr>
<tr><td colspan="2">Työn kuvaus[5]
Opinnäytetyön tavoitteena on selvittää passiivisen intermodulaation syntymistavat ja kuvata erilaiset epälineaarisuus mallit. Mitattuja tuloksia verrataan teoreettisiin malleihin ja katsotaan noudattavatko ne jotakin teoriamallia. Työssä esitellään mittausjärjestelmä ja tarkastellaan sen lineaarisuutta ja mahdollista vaikutusta mittaustuloksiin.</td></tr>
<tr><td colspan="2">Työn tavoitteet[6]
- Kuvata passiivisen intermodulaation syntymismekanismit
- Mittausjärjestelmän esittely, analysoidaan järjestelmän epälineaarisuus
- Verrataan mittaustuloksia teoreettisiin epälineaarisuus malleihin
- Tutkia, onko CW signaalien etäisyydellä (spacing) vaikutusta IM tulosten tasoon</td></tr>
<tr><td colspan="2">Tavoiteaikataulut[7]
- Alustava sisällysluettelo viikko 5
- Terio-osan katselmointi viikolla 8
- Mittausjärjestelmän analysoinnin katselmointi viikolla 10-11
- Tulosten analysoinnin katselmointi viikolla 17
- Lopullinen versio valmis 1.5.2016 (sunnuntai viikolla 17)
- Tutkintotodistus 17.5.2016</td></tr>
<tr><td colspan="2">Päiväys ja allekirjoitukset[8]</td></tr>
<tr><td>25/1/2016
Tekijän allekirjoitus
Matias Pihlman</td><td>25/1/2016
Tilaajan allekirjoitus
Marko Leinonen</td></tr>
</table>

1. Tekijän nimi, puhelinnumero ja sähköpostiosoite.
2. Työn teettävän yrityksen virallinen nimi.
3. Sen henkilön nimi ja yhteystiedot, joka yrityksessä valvoo työn suoritusta.
4. Työn nimi voi olla tässä vaiheessa työnimi, jota myöhemmin tarkennetaan.
5. Työ kuvataan lyhyesti. Siinä esitetään muun muassa työn tausta, lähtötilanne ja työssä ratkaistavat ongelmat.
6. Esitetään lyhyesti ja selvästi työn tavoitteet.
7. Esitetään projektin tavoiteaikataulu. Silloin, kun työllä on välitavoitteita, myös ne merkitään aikatauluun. Tavoiteaikataulun ja oppilaitoksen yleisaikataulun perusteella tekijä laati oman aikataulunsa.
8. Lähtötietomuistio päivätään ja sen allekirjoittavat tekijä ja tilaajan yhdyshenkilö